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Stress shielding in periprosthetic bone following a total knee replacement: Effects of implant material, design and alignment

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ABSTRACT

Periprosthetic bone strain distributions in some of the typical cases of total knee replacement (TKR) were studied with regard to the selection of material, design and the alignments of tibial components to examine which conditions are more forgiving than the others to stress shielding post a TKR. Four tibial components with two implant designs (cruciate sacrificing and cruciate retaining) and material properties (metal-backed (MB) and all-polyethylene (AP)) were considered in a specimen-specific finite element tibia bone model loaded in a neutral position. The influence of tibial material and design on the periprosthetic bone strain response was investigated under the peak loads of walking and stair descending/ascending. Two of the models were also modified to examine the effect of selected implant malalignment conditions (7° posterior, 5° valgus and 5° varus) on stress shielding in the bone, where the medio-lateral load share ratios were adjusted accordingly. The predicted increases of bone density due to implantation for the selected cases studied were also presented.

For the cases examined, the effect of stress shielding on the periprosthetic bone seems to be more significantly influenced by the implant material than by the implant geometry. Significant stress shielding is found in MB cases, as opposed to increase in bone density found in AP cases, particularly in the bones immediately beneath the baseplate. The effect of stress shielding is reduced somewhat for the MB components in the malaligned positions compared with the neutral case. In AP cases, the effect of stress shielding is mostly low except in the varus position, possibly due to off-loading of lateral condyle. Increases in bone density are found in both MB and AP cases for the malaligned conditions.

1. Introduction

For advanced degenerative conditions such as osteoarthritis (OA), total knee replacement (TKR) has proven to be the most successful intervention that reduces knee pain and restores physical function in such patients. Loosening of the tibial component is the most common cause of failures in TKR [1,2,3], typically 2–3 times more frequent than the femoral component [4,5], although the mechanisms that lead to loosening is not well understood. The predominant mode of failure in a TKR is thought to be mechanical fatigue, where articulation produces polyethylene particles that are larger and more irregular in shape than those resulted from a THA, in the latter the predominant mode of failure is thought to be abrasive and adhesive wear [6]. Fundamental to the longevity of fixation is the integrity of cement–bone interlocking [3–5]. Although periprosthetic bone density change around the components of TKR has been known to occur for some time [7–11], it is only recently that evidence has been presented regarding bone resorption in the bone–cement interdigitated region. Miller et al. [3,5] presented some postmortem retrieval studies of metal-backed cemented tibial components with time in service from 0 to 20 years. They found that 75% of the bone–cement interlock was lost within 10 years of service, with extensive bony resorption at the periphery of the tibial trays. Lavernia et al. [12] reported similar findings on autopsy-retrieved femora. Significantly, these studies are based on autopsy retrievals with time in service ranging from 1 to 22 years, where the loss of cement–bone interlocking is linked with periprosthetic bone loss.

The proximal tibial metaphysis consists of dense bone platforms, supported peripherally by an exterior cortical layer and an interior of cancellous bone. The tibial implant is mainly supported by cancellous bone. Under physiological loading conditions the medial plateau is subjected to a greater proportion of the load, and the stresses in an intact tibia are at a maximum under the surface of the joint and at the proximal diaphysis. According to Wolff's law, bone remodels in response to applied loads by

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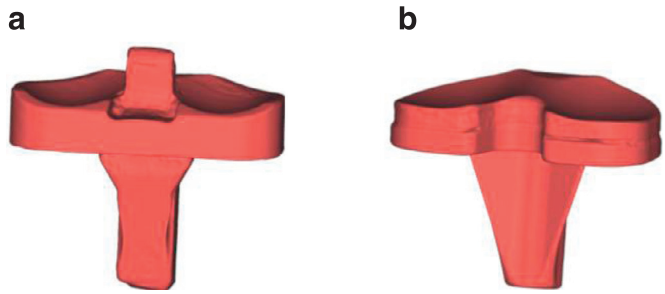

Fig. 1. The two tibial component designs considered in this study, (a) cruciate sacrificing (CS); (b) cruciate retaining (CR).

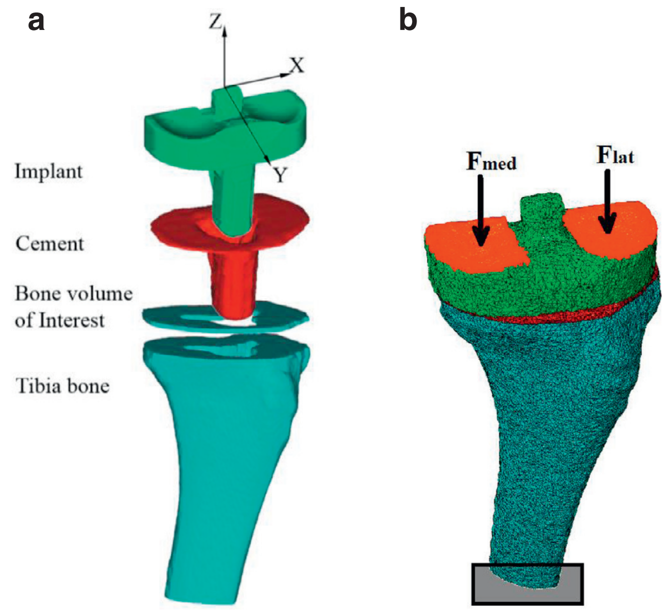

Fig. 2. (a) An illustration of the implanted tibia model, where the implant, the cement layer, a 3 mm bone volume of interest (VOI) selected at the resected surface and the tibia bone are indicated; (b) the loading and boundary conditions applied. The axial force was split into medial (F_{med}) and lateral (F_{lat}) components, and distributed on the corresponding condyles (intact) or bearing spacers (implanted) of the tibia. The ratios of medial to lateral load share were assigned based on [28,29]; the lower part of the tibia model was fully fixed.

changing its architecture. Stress shielding is likely to occur when insufficient loads are transferred to the bone due to the introduction of a stiffer implant, and bone resorption may occur. The material properties of tibial prostheses are known to influence how the stress is transferred to the underlying bone by both the tray and the stem. Given that a metal backed (MB) tray is several orders stiffer than an all-polyethylene (AP) one, far greater stress shielding is expected of MB components compared to AP components. A recent study [13] shows that the maximum compressive stress within the cancellous bone under an MB component is only a third of that under an AP component. Furthermore, loading conditions as a result of altered bone/implant condylar surface geometry, load placement and pattern due to tibial component design and malalignment may also have significant impact on periprosthetic bone stress distribution [14–17], although these factors have not been adequately studied. Whilst modern TKR instrumentation allows much improved, reproducible alignment of the components, failure cases in AP components were thought to be likely due to malalignment [18].

In the present study, detailed finite element analyses were conducted to evaluate the influence of some of the typical factors, including implant material, design and malalignment of the tibial components, on the periprosthetic bone strain response to see which conditions might be more forgiving than the others to stress shielding following a TKR. Bone responses from both the bone–cement interdigitated region, as identified by Miller et al. [3,5], and the whole tibia were considered, together with the potential bone density increase due to implantation.

2. Materials and methods

A three-dimensional finite element model of an intact proximal segment of tibial bone was developed from the CT images of a female left tibia obtained from the Visible Human Project [19] using Mimics 14.0 (Materialise, Leuven, Belgium). Two common designs of a tibial component (Zimmer NexGen Hi Flex) were considered (Fig. 1): one with cruciate sacrificing (CS), where the polyethylene liner has a central peg so it is posterior stabilised; and one with cruciate retaining (CR), where the polyethylene liner is without the central peg. The 3D geometries of the two implants were scanned using computed tomography (CT) in a STL format, constructed into solid models and virtually implanted into the proximal tibia using Boolean operations in Mimics. A cement layer, of a thickness approximately 2 mm, was introduced between the tibial component and the bone (Fig. 2(a)). The interface between the bone and the cement; and that between the component and the cement were assumed to be fully-bonded. The lower end of the tibial model was fully fixed (Fig. 2(b)) and the length of the tibial model is 150 mm.

The bone, the tibial components and the cement were simplified as linear elastic and isotropic materials. The heterogeneous properties of the bone were assigned by mapping the

Table 1
The materials properties assigned for the components of the FE models.

Component	Young's modulus (MPa)	Poisson's ratio
Bone [20–22]	$E=f(HU)$	0.3
Titanium tray [37]	110,000	0.3
Polyethylene [37]	1000	0.3
Cement [31]	2200	0.3

CT Hounsfield unit (HU) values to the elastic modulus of each bone element, using an empirical relationship from the literature [20–22]:

$$E = 2017.3 \times ((HU + 13.4)/1017)^{2.46} \quad (1)$$

The range of Young's modulus values obtained from Eq. (1) is from 124 MPa to 4823 MPa, which is within the normal range of cancellous bone in knee [23].

For each implant design (CS and CR), both AP and MB components were examined. For MB components, the material properties of the tibia tray/stem and the spacer were assumed to be titanium and polyethylene, respectively; whilst the AP component was assigned with the properties of polyethylene. The material properties used in the present study are listed in Table 1.

All four tibial components (CS–AP, CS–MB, CR–AP, CR–MB) were implanted in a neutral position to investigate, first of all, the effect of component design and material on the stress shielding of periprosthetic bone. For the neutral position the tibial plateau was cut at 0° posterior slope and 90° to the mechanical axis of the tibia [24]. In addition, the two CS components were also implanted at three malalignment positions (7° posterior, 5° valgus and 5° varus) to examine the influence of malalignment on the periprosthetic bone responses (Fig. 3). The angles were selected to be within the tolerance limits in surgical practice for bone collapse or instability [17,25].

The average peak axial contact forces of 1960 N, 2492 N and 2280 N, obtained from in vivo telemetric measurements for